

# The binary progenitor of Tycho Brahe's 1572 supernova

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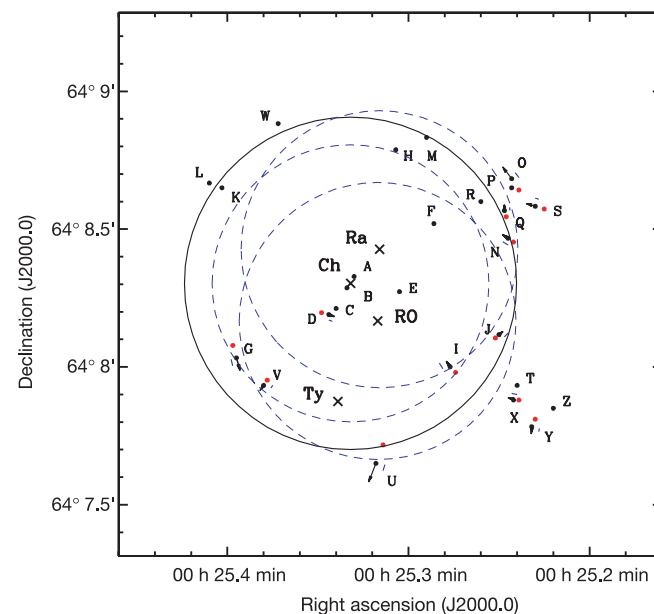
The brightness of type Ia supernovae, and their homogeneity as a class, makes them powerful tools in cosmology, yet little is known about the progenitor systems of these explosions. They are thought to arise when a white dwarf accretes matter from a companion star, is compressed and undergoes a thermonuclear explosion<sup>1–3</sup>. Unless the companion star is another white dwarf (in which case it should be destroyed by the mass-transfer process itself), it should survive and show distinguishing properties. Tycho's supernova<sup>4,5</sup> is one of only two type Ia supernovae observed in our Galaxy, and so provides an opportunity to address observationally the identification of the surviving companion. Here we report a survey of the central region of its remnant, around the position of the explosion, which excludes red giants as the mass donor of the exploding white dwarf. We found a type G0–G2 star, similar to our Sun in surface temperature and luminosity (but lower surface gravity), moving at more than three times the mean velocity of the stars at that distance, which appears to be the surviving companion of the supernova.

Tycho Brahe's supernova (that is, SN 1572) is one of the only two supernovae observed in our Galaxy that are thought to have been of type Ia (the other having been SN 1006) as revealed by the light curve, radio emission and X-ray spectra<sup>4–7</sup>.

The field that contained Tycho's supernova, relatively devoid of background stars, is favourable for searching for any surviving companion. With a Galactic latitude  $b = +1.4^\circ$ , Tycho's supernova lies 59–78 pc above the Galactic plane. The stars in that direction show a consistent pattern of radial velocities with a mean value of  $-30 \text{ km s}^{-1}$  at 3 kpc. The predictions of how the companion star would look after the impact of the supernova ejecta, if there is any companion, depend on what the star actually is. The star could be in any evolutionary stage before the explosion: main sequence, sub-giant or red giant<sup>1–3</sup>. The most salient feature of the surviving companion star should be peculiar velocities with respect to the average motion of the other stars at the same location in the Galaxy (mainly due to disruption of the binary)<sup>8</sup>, detectable through radial-velocity measurements, and perhaps also signs of the impact of the supernova ejecta. The latter can be twofold. First, mass should have been stripped from the companion and thermal energy injected into it, possibly leading to expansion of the stellar envelope that would make the star have a lower surface gravity. Second, depending on the

interaction with the ejected material, the surface of the star could be contaminated by the slowest-moving ejecta (made of Fe and Ni isotopes). If the companion's stellar envelope is radiative, such a contamination could be detectable through abundance measurements. Therefore, the observations have been designed along these lines. The star most likely to have been the mass donor of SN 1572 has to show a multiple coincidence: being at the distance of SN 1572, it has to show an unusual radial velocity in comparison to the stars at the same location (much above the velocity dispersion for its spectral type), and have stellar parameters consistent with being struck by the supernova explosion. It should also lie near the remnant centre (that is, within our search radius).

The distance to SN 1572 inferred from the expansion of the radio shell and by other methods lies around 3 kpc ( $2.83 \pm 0.79 \text{ kpc}$ )<sup>9</sup>. Such a distance, and the light-curve shape of SN 1572, are consistent with it being a normal type Ia supernova in luminosity, like those commonly found in cosmological searches<sup>9</sup>. Given the age of the supernova remnant (SNR; just 432 yr) and the lower limit to its distance, any possible companion, even if it moved at a speed of  $300 \text{ km s}^{-1}$ , could not be farther than 0.15 arcmin (9.1 arcsec) from its position at the time of the explosion<sup>8,10</sup>. But the search radius



**Figure 1** Positions and proper motions of stars. Positions are compared with three centres: the Chandra (Ch) and ROSAT (RO) geometrical centres of the X-ray emission, and that of the radio emission (Ra). Dashed lines indicate circles of 0.5 arcmin around those centres. The supernova position reconstructed from Tycho Brahe's measurements (Ty) is also shown, though merely for its historical interest<sup>21</sup>. The radius of the remnant is about 4 arcmin and the SNR is quite spherically symmetric, with a fairly good coincidence between radio and continuum X-ray emission<sup>8,22,23</sup>. However, there is a 0.56 arcmin displacement along the east–west axis between the radio emission and the high-energy continuum in the 4.5–5.8 keV band observed by XMM–Newton in the position of the western rim<sup>23</sup> (Supplementary Note 1). Such asymmetry amounts to a 14% offset along the east–west axis. In SNRs from core-collapse supernovae (type II supernovae), up to a 15% discrepancy between the location of the compact object and the geometric centre is found in the most symmetric cases<sup>24</sup>. On the basis of the above considerations, in our search we cover 15% of the innermost radius (0.65 arcmin) of the SNR around the Chandra centre of SN 1572. The companion star, if there is any, is unlikely to be outside this area (solid line). The proper motions of the stars measured from HST WFPC2 images are represented by arrows, their lengths indicating the total displacements between AD 1572 and present. Error bars are shown by parallel segments. Red circles are the extrapolated positions of the stars back to AD 1572. Star Tycho G displays a high proper motion, corresponding to the highest tangential velocity in the field, as both stars U and O are at much shorter distances (see Supplementary Methods).

**Table 1.** Typical apparent magnitudes, proper motions, radial velocities, and maximum angular distance from explosion site (after  $10^3$  yr) of SNeIa companions

Companion type and distance	$m_V$	$\pi$ (arcsec yr $^{-1}$ )	$v_r$ (km s $^{-1}$ )	$\theta$ (arcmin)
Main sequence				
1 kpc	15.1	0.067	320	1.6
5 kpc	18.6	0.013	320	0.3
Subgiant				
1 kpc	12.6	0.038	180	0.9
5 kpc	16.1	0.008	180	0.2
Red giant				
1 kpc	10.5	0.015	70	0.4
5 kpc	14.0	0.003	70	0.1

## 2 SN 1572

SN 1572 (Tycho Brahe’s supernova) is close to the Galactic plane ( $b = +1.4^\circ$ ). The field of the supernova is  $3.8'$  in radius. In SN 1572 the radio shell is very regular and early radio and optical expansion measurements have found similar results on the ejecta expansion rate. The distance inferred by the expansion of the radio shell and by other methods lies between 2.25 and 4.5 kpc (Strom, Goss & Shaver 1982).

An estimate of the center is possible with an uncertainty less than 10 % of the radio shell. Therefore, it seemed a good strategy to complete observations down to a magnitude limit  $m_R \sim 23$  of the stars within  $0.7'$  of the center. In Figure 1 we show the spectra of some of the stars near the center of the remnant. A red giant is very near the geometrical center of SN 1572. Other stars in the vicinity range from supergiants to WDs.

We have obtained spectra with high enough resolution to allow detection of motions in the radial direction. Our spectra correspond to different epochs and this allows an additional check of variation of the velocities in those directions. Spectra were obtained with ISIS and UES at the William Herschel Telescope and with ESI at the Keck Telescope (see Table 2 for the observations).

Table 1: Visual estimates of Tycho’s Supernova

Date		Phase	Description		
	(days)	Adopted		$m_V$	Ref.
1572 Nov 2	Nov 2	-	No detection	$> 5$	<sup>1</sup>
1572 Nov	Nov 11	-10	Somewhat brighter than Jupiter and almost equal to the Morning Star	$-3. \pm 0.2$	<sup>2</sup>
1572 Nov	Nov 11	-10	Equalled Venus when this planet was at maximum brightness	$-3. \pm 0.2$	<sup>3</sup>
1572 Nov 16,17	Nov 16 $\pm 1$ -5 $\pm 1$		Almost as bright as Venus and Jupiter	$-4.0 \pm 0.3$	<sup>4</sup>
1572 Dec	Dec 15 $\pm 7$ 24 $\pm 7$		About as bright as Jupiter	$-2.4 \pm 0.3$	<sup>6</sup>
1573 Jan 7	Jan 7	47	Already fainter than Jupiter	$> -2.$	<sup>7</sup>
1573 Jan	Jan 15 $\pm 7$ 55 $\pm 7$		A little fainter than Jupiter and brighter than the brighter stars of first mag	$-1.4 \pm 0.4$	<sup>7</sup>
1573 Feb–Mar	Mar 2 $\pm 14$ 101 $\pm 14$		Equal to brighter stars of first mag	$+0.3 \pm 0.2$	<sup>8</sup>
1573 Apr–May	May 1 $\pm 14$ 161 $\pm 14$		Equal to stars of second mag.	$+1.6 \pm 0.5$	<sup>9</sup>
1573 July–Aug	Aug 1 $\pm 14$ 253 $\pm 14$		Equal to $\alpha, \beta, \gamma, \delta$ Cas	$+2.5 \pm 0.2$	<sup>10</sup>
1573 Oct–Nov	Nov 1 $\pm 14$ 345 $\pm 14$		Equal to stars of fourth mag. (among Cassiopea stars)	$+4.0 \pm 0.2$	<sup>11</sup>
1573 Nov	Nov 15 $\pm 7$ 359 $\pm 7$		Equal to $\kappa$ Cas	$+4.2 \pm 0.2$	<sup>12</sup>
1573 Dec–1574 Jan	Jan 1 $\pm 14$ 406 $\pm 14$		Hardly exceeding stars of fifth mag.	$+4.7 \pm 0.2$	<sup>13</sup>
1574 Feb	Feb 15 $\pm 7$ 451 $\pm 7$		Equal to stars of sixth mag.	$+5.3 \pm 0.4$	<sup>13</sup>

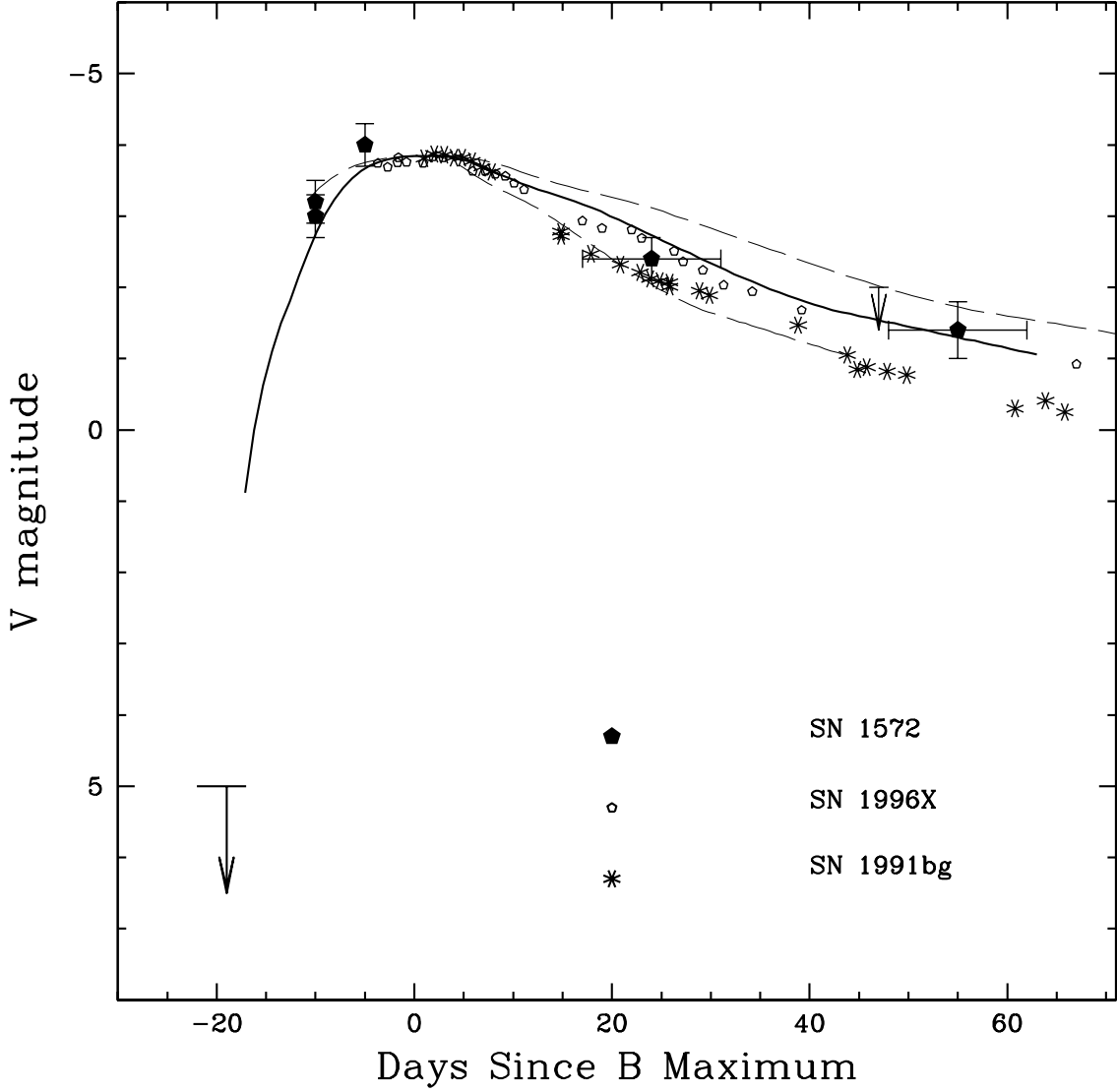


Fig. 1.— The visual light curve of SN 1572 till 60 days. The solid curve is the V light curve of a  $s = 0.9$  SNIa, which gives the best account for the decline. Such *stretch factor* is typical of normal SNe Ia. We show for comparison the V light curve of the normal SNIa SN 1996X, whose stretch factor is  $s = 0.889$  and of the fast-declining SN 1991bg. SN 1572 was significantly slower than SN 1991bg. The light curves plotted in dashed lines are the templates of 91bg-type events and 91T-like events, which depart significantly from the data.

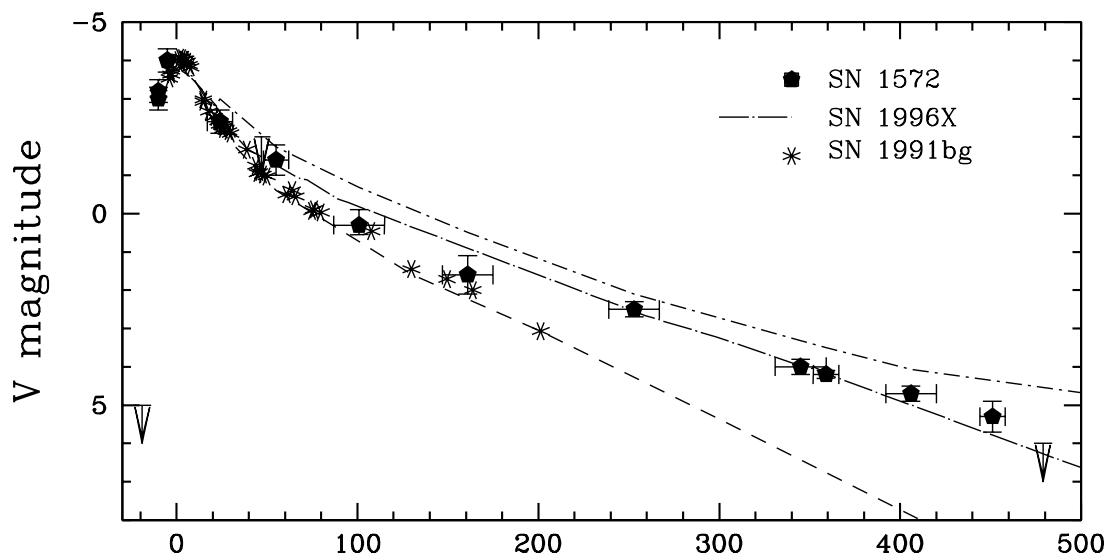


Fig. 2.— The visual light curve of SN 1572 till 500 days. Its late rate of decline is the one of normal SNIa. It is very similar to the decline of the  $s = 0.889$  SN 1996X. The visual data of SN1991bg and the template light curves of this SNIa and SN1991T are shown for comparison.

Table 2: Colors of Tycho’s Supernova

Date	Phase	Description	B – V	Observer
	Adopted		Adopted	Reference
1572 Nov	Nov 21 $\pm 7$ -6 $\pm 7$	Like Venus (B – V = 0.83) and Jupiter (B – V = 0.82)	0.82 $\pm$ 0.25	<sup>1</sup>
1572 Dec	Dec 1 $\pm 5$ 10 $\pm 5$	Yellowish	1.0 $\pm$ 0.25	<sup>2</sup>
1572 Nov-Dec	Dec 2 <sup>7</sup> <sub>-22</sub> 11 <sup>7</sup> <sub>-22</sub>	Between Saturn (B – V = 1.04) and Mars (B–V)=1.36, closer to Mars	1.2 $\pm$ 0.25	<sup>3</sup>
1572 Jan	Jan 1 $\pm 7$ 41 $\pm 7$	Like Aldebaran (B–V=1.52)	1.52 $\pm$ 0.25	<sup>4</sup>
1573 Jan	Jan 15 $\pm 7$ 55 $\pm 7$	Similar to Mars (B – V = 1.36)	1.36 $\pm$ 0.2	<sup>5</sup>
1573 Feb	Feb 28 $\pm 7$ 99 $\pm 7$	Return to original	0.82 $\pm$ 0.25	<sup>6</sup>
1573 May	May 15 $\pm 7$ 175 $\pm 7$	Like the original (B – V = 0.83)	0.82 $\pm$ 0.25	<sup>7</sup>

## NOTES TO TABLE 2

<sup>1</sup>Various reports (see Baade 1945) give a color similar to the colors of Venus and Jupiter.

<sup>2</sup> Tycho Brahe (1603a) states that after maximum it became yellowish in color. By comparison to the description as whitish (like Jupiter) and red like Aldebaran, we assign B–V =1.0  $\pm$ 0.25.

<sup>3</sup> Muñoz (1573) states that the color was between those of Saturn and Mars, closer to Mars. One could identify then the color as 1.2  $\pm$  0.1. Unfortunately, there is ambiguity in the

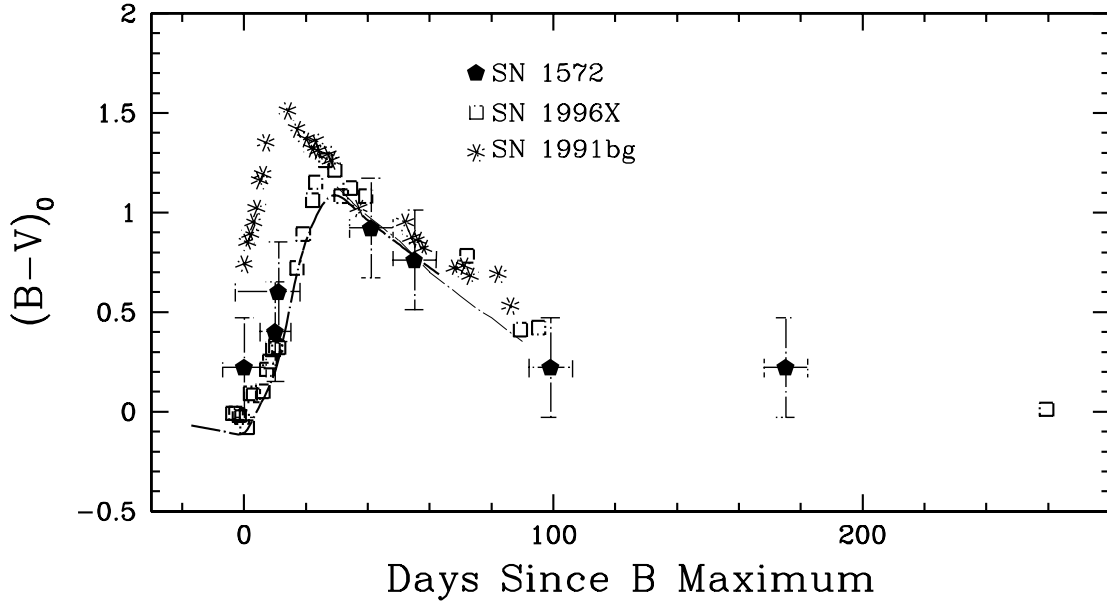
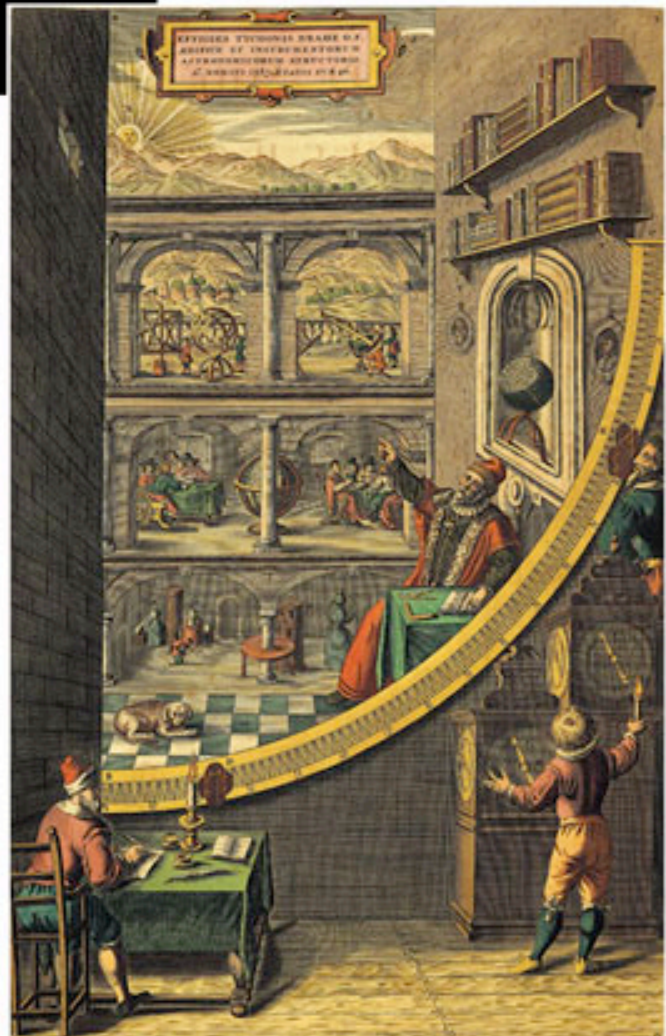
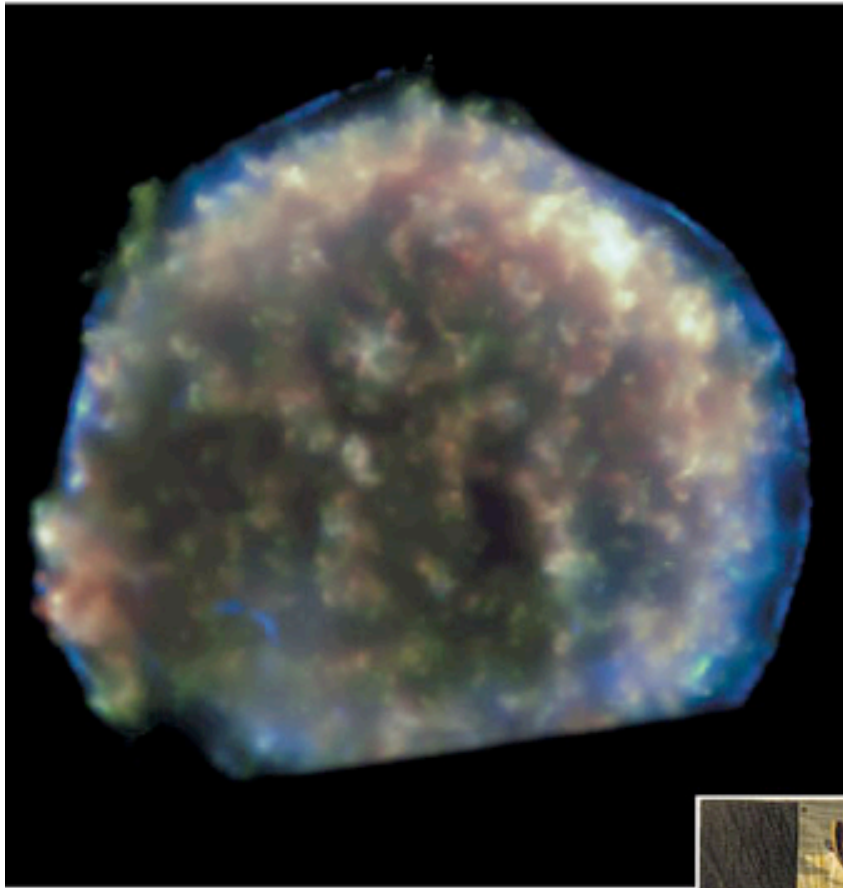


Fig. 3.— Color evolution of SN 1572 corrected from extinction as compared with normal SNe Ia and SN 1991bg. SN 1572 is consistent with the color evolution of a  $s = 0.9$  SN Ia (template for this stretch is plotted as dot-dashed curve). SN 1996X has been corrected for its very small reddening  $E(B-V)=0.01 \pm 0.02$  as well as SN 1991bg ( $E(B-V)=0.03 \pm 0.05$ ) (Ph99).

Table 3: SN 1572

Parameter	$s$	$\Delta m(V)_{20}$	$\Delta m(V)_{60}$	$\gamma_{(V)}^{late}$	$B - V_0$
SN 1572	$0.9 \pm 0.05$	$1.1 \pm 0.4$	$2.6 \pm 0.6$	$1.6 \pm 0.04$	$0.22 \pm 0.25$
SN 1991bg-like	0.62	1.68	3.3	2.7	0.6
SN 1991T-like	1.2	0.72	2.46	1.68	-0.1
Normal <sup>1</sup>	0.9	0.9	2.8	1.7	0.0

Normal SNe Ia of  $s = 0.9$ . Whereas the  $\Delta m(V)_{20}$  is not well defined for SN 1572 due to a lack of accurate observations in the week around the maximum, the rate of decline in terms of stretch can be well determined by fitting premaximum and postmaximum up to 60 days.



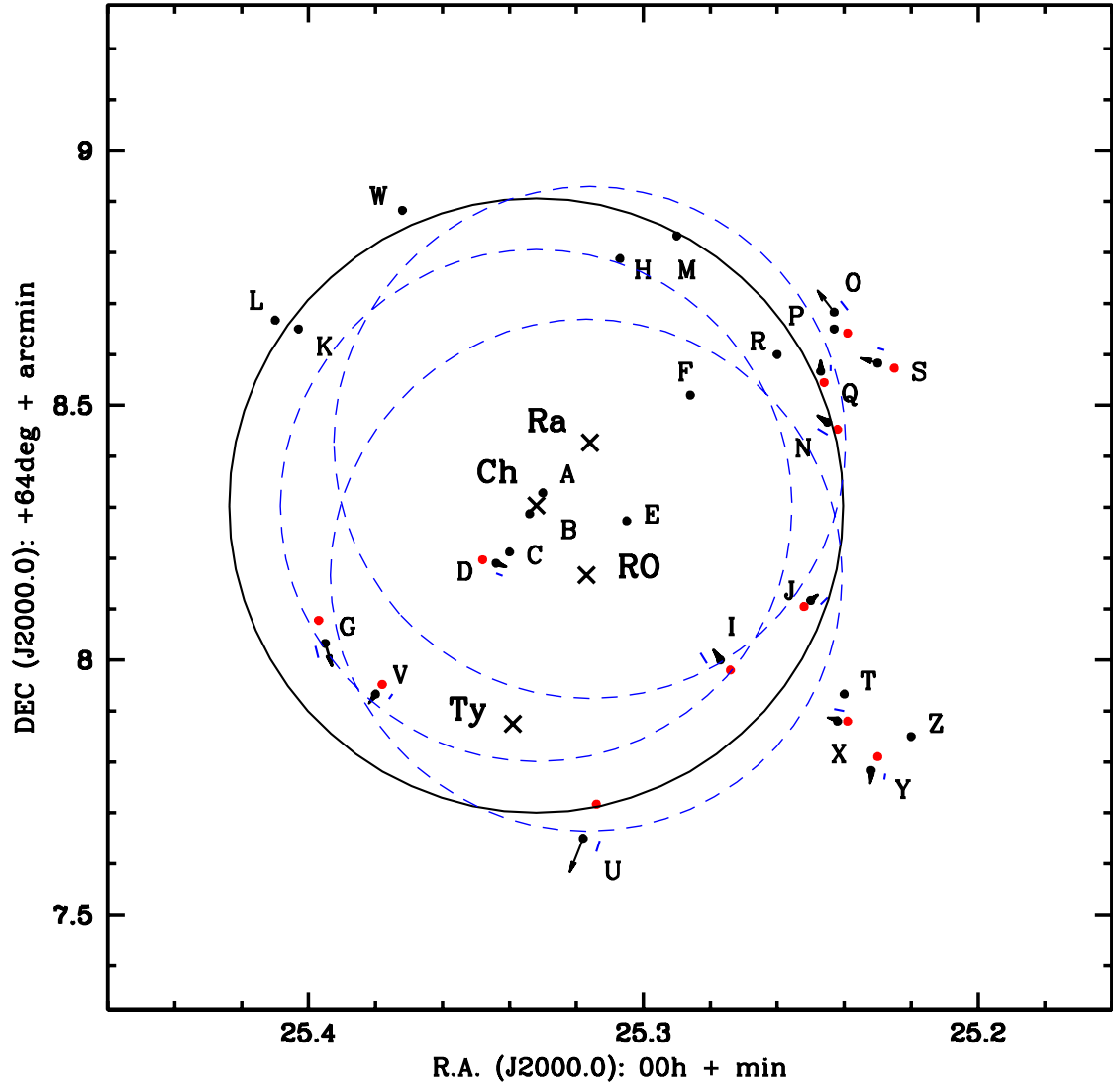


Fig. 1.—

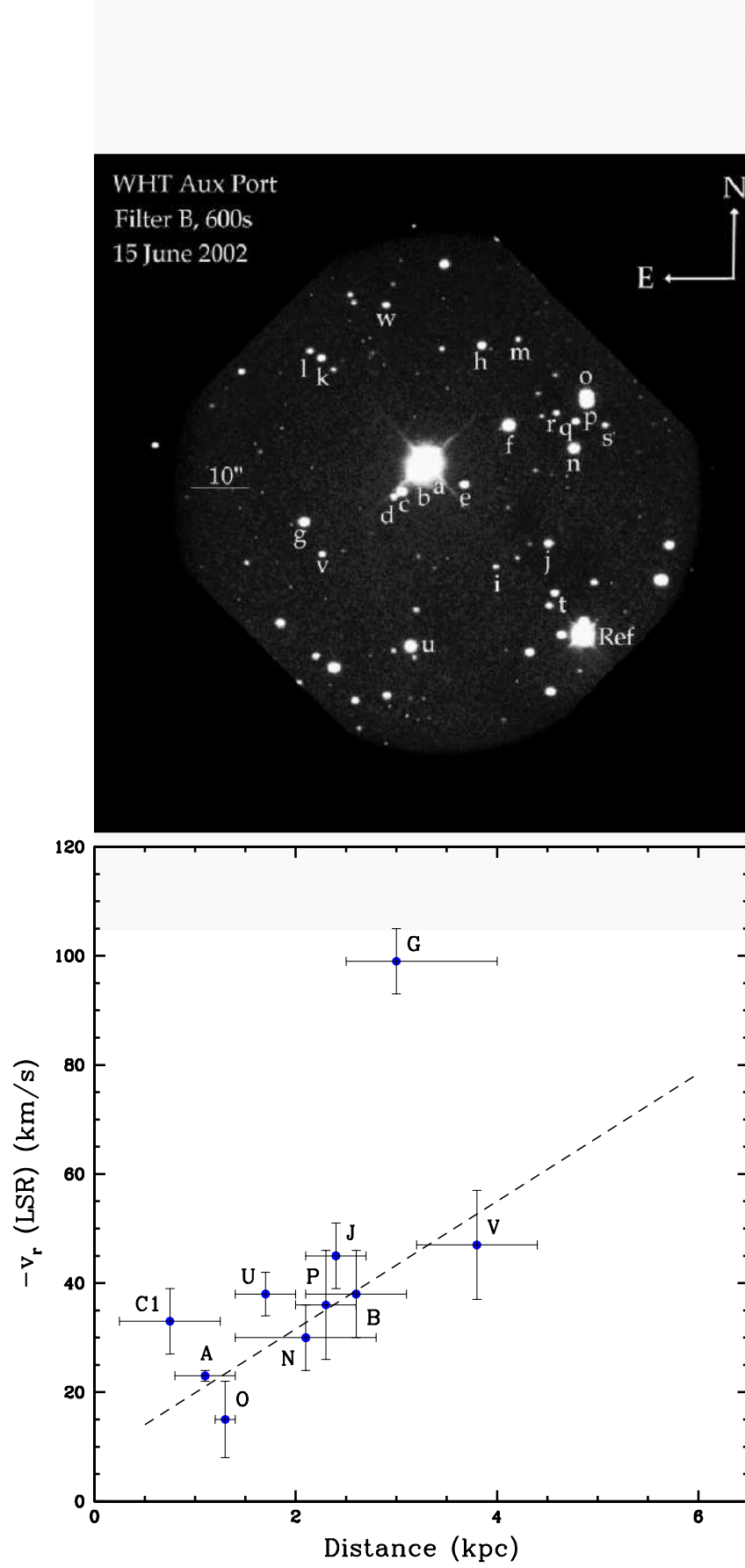


Table 1: **Table 1. Characteristics of the supernova companion candidates**

Star	$\theta$ (arcsec)	Spec. type & lum. class	$T_{eff}$ (K)	$\log g$ (c.g.s.)	E(B–V) (mag.)	d (kpc)
Tycho A	1.6	K0–K1 III	4750	$2.5^{+0.5}_{-0.5}$	$0.55^{+0.05}_{-0.05}$	$1.1^{+0.3}_{-0.3}$
Tycho B	1.5	A8–A9 V	7500	$4.5^{+0.5}_{-0.5}$	$0.60^{+0.05}_{-0.05}$	$2.6^{+0.5}_{-0.5}$
Tycho C1	6.5	K7 V	4000	$4.5^{+0.5}_{-0.5}$	$0.5^{+0.1}_{-0.1}$	$0.75^{+0.5}_{-0.5}$
Tycho C2	6.5	F9 III	6000	$2.0^{+0.5}_{-0.5}$	$0.6^{+0.1}_{-0.1}$	$> 20$
Tycho D	8.4	M1 V	3750	$4.5^{+0.5}_{-0.5}$	$0.6^{+0.3}_{-0.3}$	$0.8^{+0.3}_{-0.2}$
Tycho E	10.6	K2–K3 III	4250	$2.0^{+0.5}_{-0.5}$	$0.60^{+0.10}_{-0.10}$	$> 20$
Tycho F	22.2	F9 III	6000	$2.0^{+0.5}_{-0.5}$	$0.54^{+0.22}_{-0.22}$	$> 10$
Tycho G	29.7	G2 IV	5750	$3.5^{+0.5}_{-0.5}$	$0.60^{+0.05}_{-0.05}$	$3.0^{+1.0}_{-0.5}$
Tycho H	30.0	G7 III	5000	$3.0^{+0.5}_{-0.5}$	$0.60^{+0.09}_{-0.09}$	$> 13$
Tycho J	33.9	K1 V	5000	$4.5^{+0.5}_{-0.5}$	$0.58^{+0.12}_{-0.11}$	$2.4^{+0.3}_{-0.2}$
Tycho K	35.0	F9 III	6000	$2.0^{+0.5}_{-0.5}$	$0.60^{+0.10}_{-0.10}$	$> 10$
Tycho N	35.4	G0 V	6000	$4.5^{+0.5}_{-0.5}$	$0.62^{+0.08}_{-0.07}$	$2.1^{+0.7}_{-0.7}$
Tycho V	29.2	K3 V	4750	$4.5^{+0.5}_{-0.5}$	$0.60^{+0.10}_{-0.10}$	$3.8^{+0.6}_{-0.6}$

**Supplementary Table 3. Magnitudes and radial velocities of the stars**

Star	$\theta$ (arcsec)	B (mag.)	V (mag.)	R (mag.)	$v_r$ (km/s)
A	1.6	$14.82^{+0.03}_{-0.03}$	$13.29^{+0.03}_{-0.03}$	$12.24^{+0.03}_{-0.03}$	$-23^{+1}_{-1}$
B	1.5	$16.35^{+0.03}_{-0.03}$	$15.41^{+0.03}_{-0.03}$	$15.11^{+0.10}_{-0.10}$	$-38^{+8}_{-8}$
C*	6.5	$21.06^{+0.12}_{-0.12}$	$19.06^{+0.05}_{-0.05}$	$17.77^{+0.03}_{-0.03}$	$-33^{+6}_{-6}$
D	8.4	$22.97^{+0.28}_{-0.28}$	$20.70^{+0.10}_{-0.10}$	$19.38^{+0.06}_{-0.06}$	—
E	10.6	$21.24^{+0.13}_{-0.13}$	$19.79^{+0.07}_{-0.07}$	$18.84^{+0.05}_{-0.05}$	$-26^{+18}_{-18}$
F	22.2	$19.02^{+0.05}_{-0.05}$	$17.73^{+0.03}_{-0.03}$	$16.94^{+0.03}_{-0.03}$	$-34^{+11}_{-11}$
G	29.7	$20.09^{+0.08}_{-0.08}$	$18.71^{+0.04}_{-0.04}$	$17.83^{+0.03}_{-0.03}$	$-99^{+6}_{-6}$
H	30.0	$21.39^{+0.14}_{-0.14}$	$19.80^{+0.07}_{-0.07}$	$18.78^{+0.05}_{-0.05}$	$-71^{+10}_{-10}$
J	33.9	$21.15^{+0.12}_{-0.12}$	$19.74^{+0.07}_{-0.07}$	$18.84^{+0.05}_{-0.05}$	$-45^{+6}_{-6}$
K	35.0	$21.64^{+0.15}_{-0.15}$	$20.11^{+0.08}_{-0.08}$	$19.15^{+0.05}_{-0.05}$	$-33^{+10}_{-10}$
N	35.4	$19.59^{+0.06}_{-0.06}$	$18.29^{+0.04}_{-0.04}$	$17.47^{+0.03}_{-0.03}$	$-30^{+6}_{-6}$
V	29.2	$23.32^{+0.33}_{-0.33}$	$21.41^{+0.13}_{-0.13}$	$20.20^{+0.08}_{-0.08}$	$-47^{+10}_{-10}$
O	41.5	$18.62^{+0.04}_{-0.04}$	$17.23^{+0.03}_{-0.03}$	$16.37^{+0.03}_{-0.03}$	$-15^{+7}_{-7}$
P	40.4	$18.84^{+0.10}_{-0.10}$	$17.61^{+0.03}_{-0.03}$	$16.78^{+0.03}_{-0.03}$	$-36^{+10}_{-10}$
U	39.5	$19.03^{+0.05}_{-0.05}$	$17.73^{+0.03}_{-0.03}$	$16.95^{+0.03}_{-0.03}$	$-38^{+4}_{-4}$

Angular distances from Chandra’s geometrical X-ray centre, BVR apparent magnitudes and radial velocities (LSR) for the sample of SN companion candidates. Radial velocities have been measured from the wavelength shifts of several absorption lines in each observed spectrum (see Supplementary Table 1). \*Data are for the unresolved pair. From the HST data, the brighter, bluer component has magnitudes  $B = 21.28$ ,  $V = 19.38$ ,  $R = 18.10$  while the fainter, redder component has  $B = 22.91$ ,  $V = 20.53$ ,  $R = 19.23$ .

Table 1: **Supplementary Table 2.** Hubble Space Telescope data sets used for proper motions measurements

Dataset	Date	Filter	Exposure Time	Instrument
U42H0106R	1999-02-15	F675W	10.0 s	WFPC2
U42H010BR	1999-02-15	F555W	10.0 s	WFPC2
U42H010CR	1999-02-15	F555W	700.0 s	WFPC2
U42H010DR	1999-02-15	F555W	700.0 s	WFPC2
U42H010ER	1999-02-15	F555W	700.0 s	WFPC2
U42H010FR	1999-02-15	F555W	700.0 s	WFPC2
U51B0101R	1999-10-02	F675W	10.0 s	WFPC2
U51B0102R	1999-10-02	F675W	900.0 s	WFPC2
U51B0103R	1999-10-02	F675W	900.0 s	WFPC2
U51B0104R	1999-10-02	F675W	900.0 s	WFPC2
U51B0105R	1999-10-02	F675W	900.0 s	WFPC2
U8S90101M	2003-11-08	F555W	400.0 s	WFPC2
U8S90102M	2003-11-08	F555W	400.0 s	WFPC2
U8S90103M	2003-11-08	F555W	400.0 s	WFPC2
U8S90104M	2003-11-08	F555W	400.0 s	WFPC2
U8S90105M	2003-11-08	F555W	1.0 s	WFPC2
U8S90106M	2003-11-08	F555W	1.0 s	WFPC2
U8S90107M	2003-11-08	F555W	1.0 s	WFPC2
U8S90108M	2003-11-08	F555W	1.0 s	WFPC2
U8S90109M	2003-11-08	F555W	1.0 s	WFPC2
U8S9010AM	2003-11-08	F555W	1.0 s	WFPC2
U8S9010BM	2003-11-08	F555W	0.2 s	WFPC2
U8S9010CM	2003-11-08	F555W	0.2 s	WFPC2
U8S9010DM	2003-11-08	F555W	0.2 s	WFPC2
U8S9010EM	2003-11-08	F555W	0.2 s	WFPC2
U8S9010FM	2003-11-08	F555W	0.2 s	WFPC2
U8S9010GM	2003-11-08	F555W	0.2 s	WFPC2

Dataset	Date	Filter	Exposure Time	Instrument
U8S9010HM	2003-11-08	F555W	100.0 s	WFPC2
U8S9010IM	2003-11-08	F555W	100.0 s	WFPC2
U8S9010JM	2003-11-08	F555W	100.0 s	WFPC2
U8S9010KM	2003-11-08	F555W	100.0 s	WFPC2
U8S9010LM	2003-11-08	F555W	100.0 s	WFPC2
U8S90201M	2003-11-06	F555W	400.0 s	WFPC2
U8S90202M	2003-11-06	F555W	400.0 s	WFPC2
U8S90203M	2003-11-06	F555W	400.0 s	WFPC2
U8S90204M	2003-11-06	F555W	400.0 s	WFPC2
U8S90205M	2003-11-06	F555W	1.0 s	WFPC2
U8S90206M	2003-11-06	F555W	1.0 s	WFPC2
U8S90207M	2003-11-06	F555W	1.0 s	WFPC2
U8S90208M	2003-11-06	F555W	1.0 s	WFPC2
U8S90209M	2003-11-06	F555W	1.0 s	WFPC2
U8S9020AM	2003-11-06	F555W	1.0 s	WFPC2
U8S9020BM	2003-11-06	F555W	0.2 s	WFPC2
U8S9020CM	2003-11-06	F555W	0.2 s	WFPC2
U8S9020DM	2003-11-06	F555W	0.2 s	WFPC2
U8S9020EM	2003-11-06	F555W	0.2 s	WFPC2
U8S9020FM	2003-11-06	F555W	0.2 s	WFPC2
U8S9020GM	2003-11-06	F555W	0.2 s	WFPC2
U8S9020HM	2003-11-06	F555W	100.0 s	WFPC2
U8S9020IM	2003-11-06	F555W	100.0 s	WFPC2
U8S9020JM	2003-11-06	F555W	100.0 s	WFPC2
U8S9020KM	2003-11-06	F555W	100.0 s	WFPC2
U8S9020LM	2003-11-06	F555W	100.0 s	WFPC2

Table 2: **Supplementary Table 2 (cont.)** The data from 1999 correspond to *HST* programmes *GO6435* and *GO7405*. The data from 2004 correspond to *GO9729*.

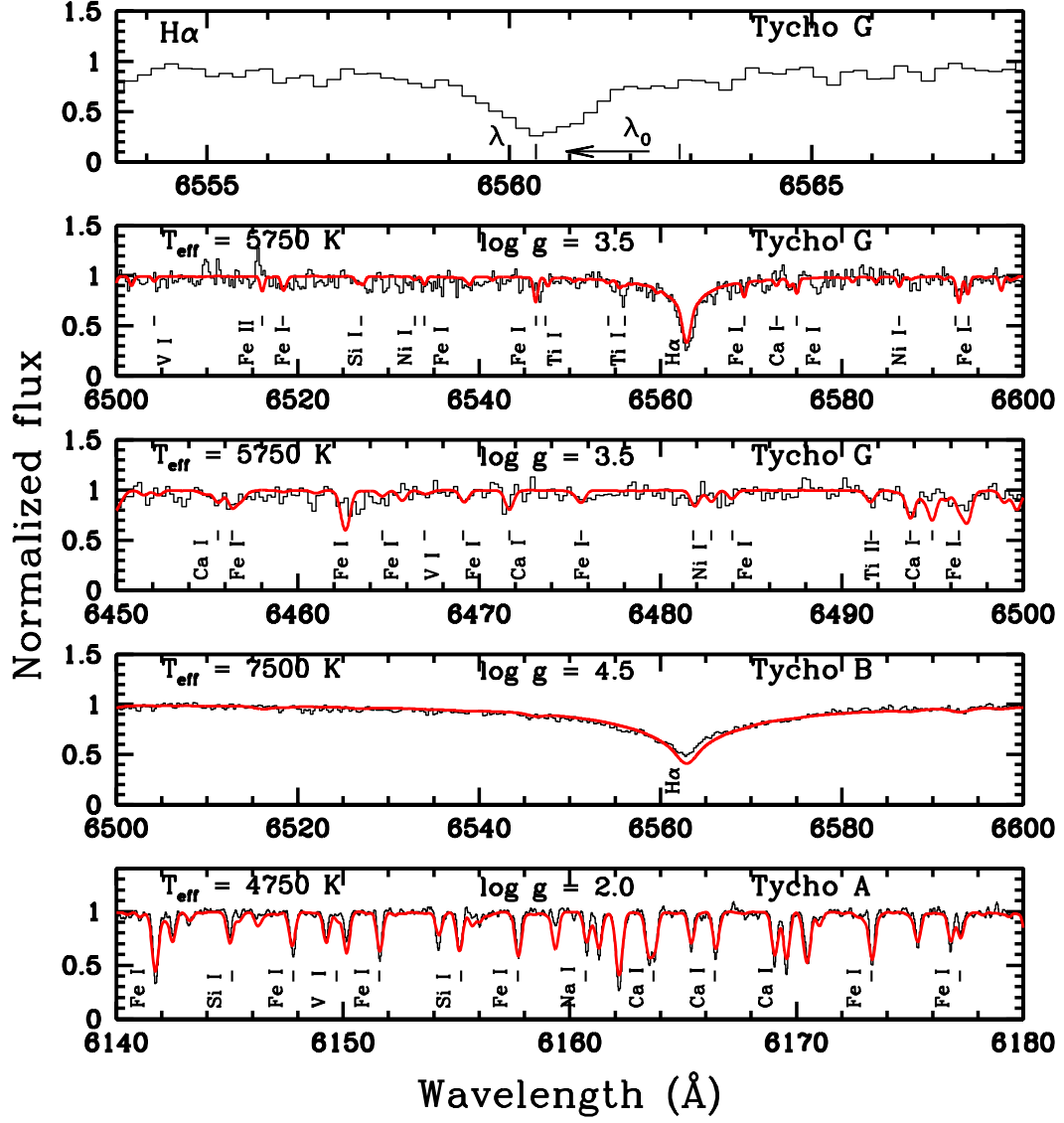
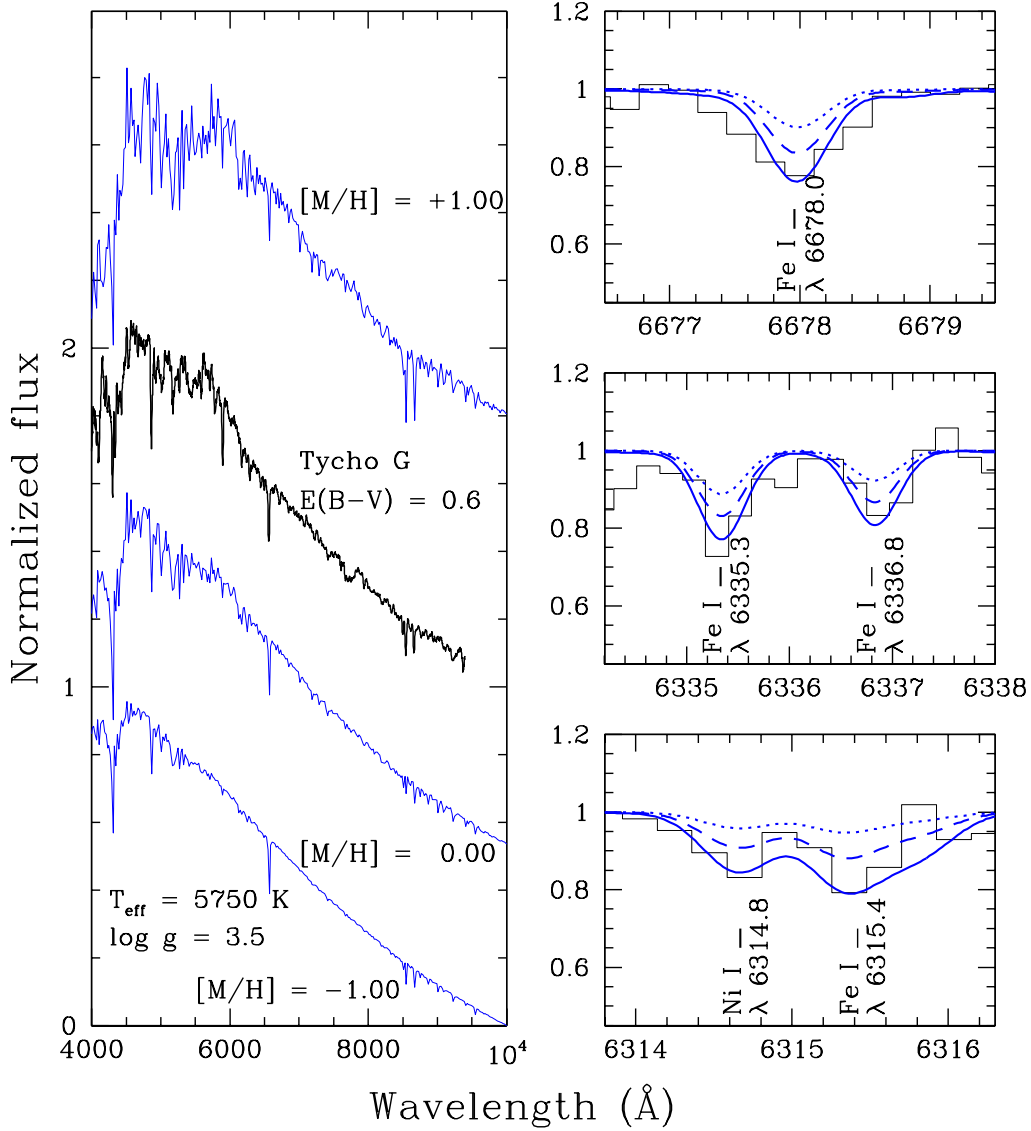


Fig. 3.—



**Supplementary Figure 1.** Spectra of Tycho G showing it to be a subgiant not belonging to the halo population. (Right panel) Several fits to Fe and Ni lines in Tycho G for solar abundances (bold) and abundances  $[Fe/H] = -0.5$  (dashed line) and  $[Fe/H] = -1$  (dotted line). This star does not belong to the halo population: it shows solar metallicities in Fe and Ni. The observed spectra were obtained with ISIS at the WHT. (Left panel) A low-resolution spectrum over a wide wavelength range was obtained with LRIS at the Keck